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Published in:
EMS Annual Meeting Abstracts

Publication date:
2016

Citation (APA):
Volker, P., Badger, J., & Hahmann, A. N. (2016). Dynamical and statistical-dynamical modelling of wind farm flows with WRF. In *EMS Annual Meeting Abstracts* (Vol. 13)

Dynamical and statistical-dynamical modelling of wind farm flows with WRF

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DTU Wind Energy (Risø Campus)

Mesoscale model physics + Turbines

A turbine can be described as a drag device. It effects the:

- RANS equations (ensemble average with overline)

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u_i' u_j'}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} - \varepsilon_{i3k} f \overline{u}_k - \delta_{i3} g + \overline{f}_{d_i}$$

- and TKE equation

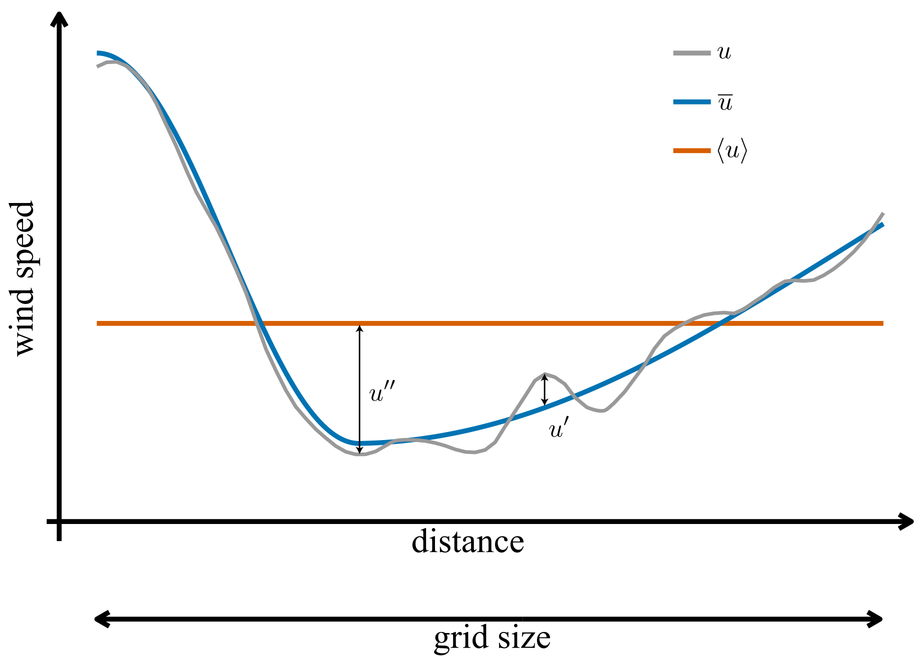
$$\frac{\partial \overline{e}}{\partial t} + \overline{T} = \overline{p}_s + \overline{p}_b - \epsilon + \overline{p}_t$$

Turbine relevant terms are $\begin{cases} \overline{f}_{d_i} & \text{Drag force} \\ \overline{p}_t & \text{Turbine induced turbulence} \end{cases}$

Considering the model discretisation

Discretisation implies spatial averaging $\langle\ \rangle$ of the RANS equations

- The drag force in spatial averaged RANS equations becomes $\langle \overline{f}_d \rangle$
- The additional TKE term $\langle \overline{p}_t \rangle$ depends on the definition of fluctuations:



(1) around spatial average: $\langle \overline{u'' f_d''} \rangle$

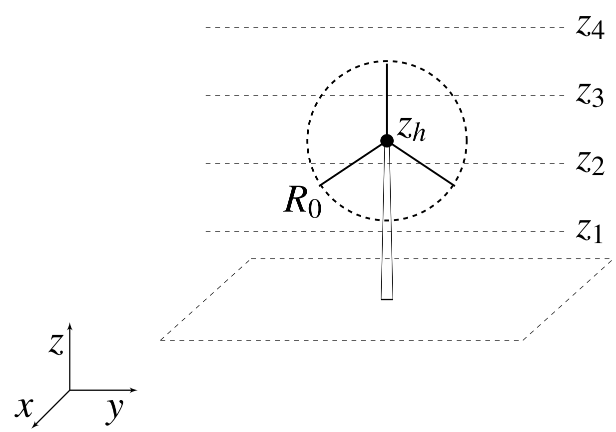
(2) around ensemble average: $\langle \overline{u' f_d'} \rangle$

Method (1) Implemented in WRF (WRF-WF)

At the turbine blade levels:

- it applies a local drag force:

$$\langle \overline{f}_d \rangle = -\rho \, c_t \, A_0 \, \langle \overline{u} \rangle^2 / 2$$



- and injects:

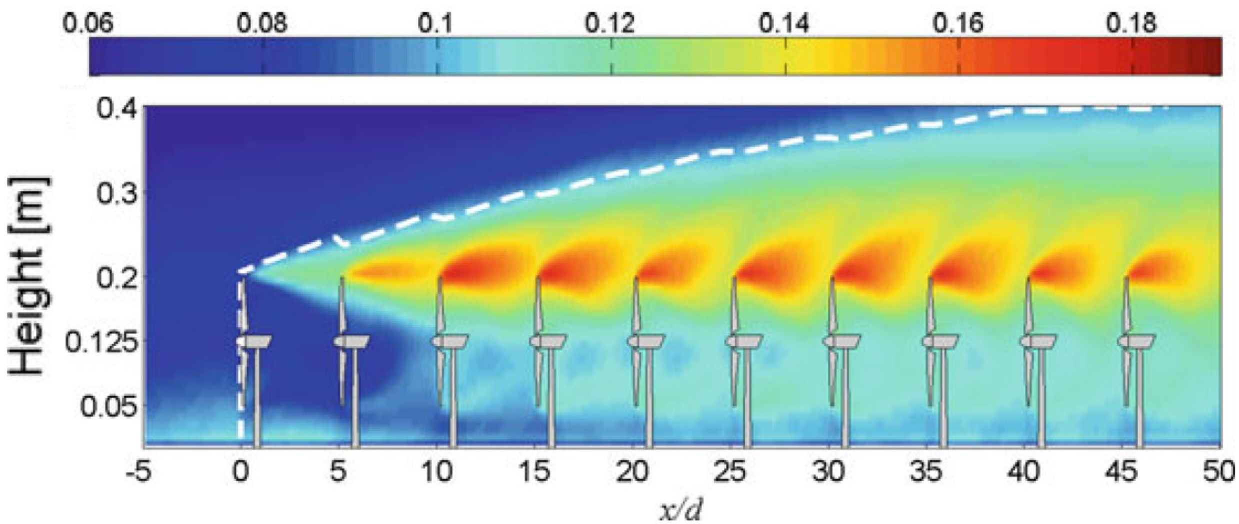
$$\langle \overline{p}_t \rangle = \langle \overline{u'' f_d''} \rangle = \rho \, A_0 \, (c_t - c_p) \langle \, \overline{|u|} \, \rangle^3 / 2 \quad \begin{cases} c_t & \text{Thrust coefficient} \\ c_p & \text{Power coefficient} \\ A_0 & \text{Rotor area} \end{cases}$$

Fitch, A. C., Olson, J. B., Lundquist, J. K., Dudhia, J., Gupta, A., Michalakes, J., and Barstad, I.: Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model, *Mon. Weather Rev.*, 2012

Motivation for a different approach

- Within a grid-cell the wake expands
- TKE mostly generated by shear $\langle \overline{p}_s \rangle$, which is part of the TKE equation

LES simulation: σ_u/U_h



Source: Wu and Porté-Agel (2013)

However: Horizontal resolution in the mesoscale model is too coarse to resolve the wake expansion

Approach: Explicit description of the unresolved wake

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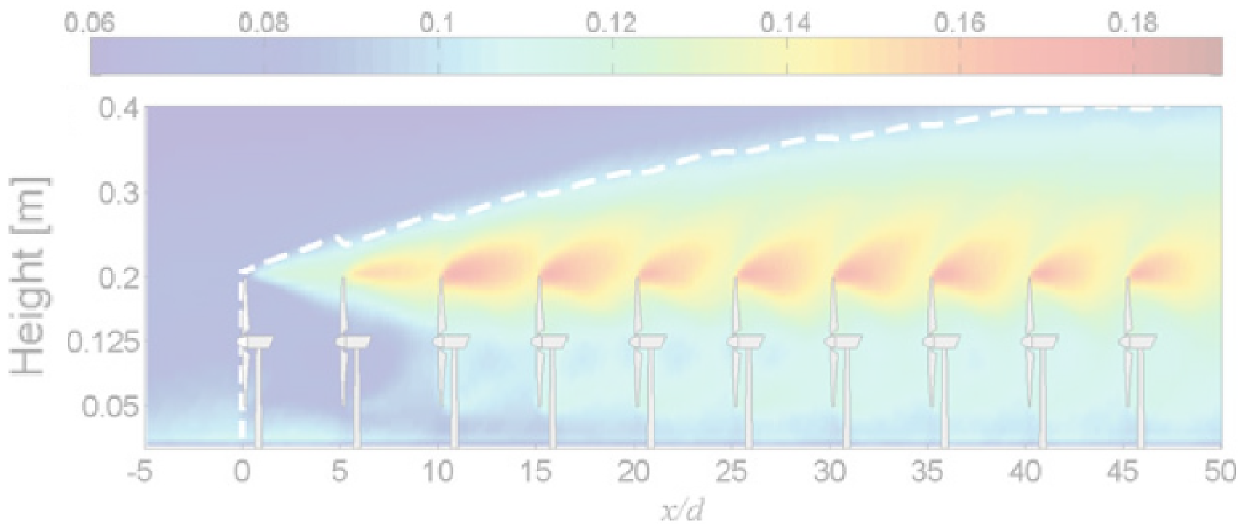


Source: Wu and Porté-Agel (2013)

However: Horizontal resolution in the mesoscale model is too coarse to resolve the wake expansion

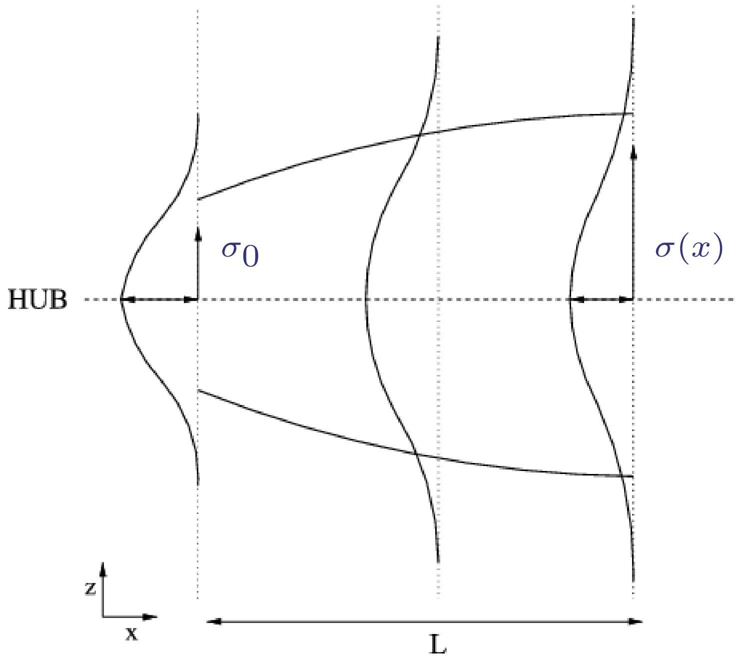
Approach: Explicit description of the unresolved (SGS) wake

Method (2) Explicit wake Parametrisation (EWP)

- Applies a spatial averaged drag force (conserving the total drag):

$$\langle \overline{f}_d \rangle = -\sqrt{\frac{\pi}{8}} \frac{c_t \, r_o^2 \, \overline{u}_o^2}{\Delta x \, \Delta y \, \sigma_e} \exp\left[-\frac{1}{2}\left(\frac{z-h}{\sigma_e}\right)^2\right]$$

Sketch of the wake development within a grid-cell:



$$\sigma^2(x) = \frac{2K_m}{U_0} x + \sigma_0^2$$

- $\langle \overline{u' f_d'} \rangle << \langle \overline{u'' f_d''} \rangle$. Thus TKE is only injected by shear $\langle \overline{p}_s \rangle$

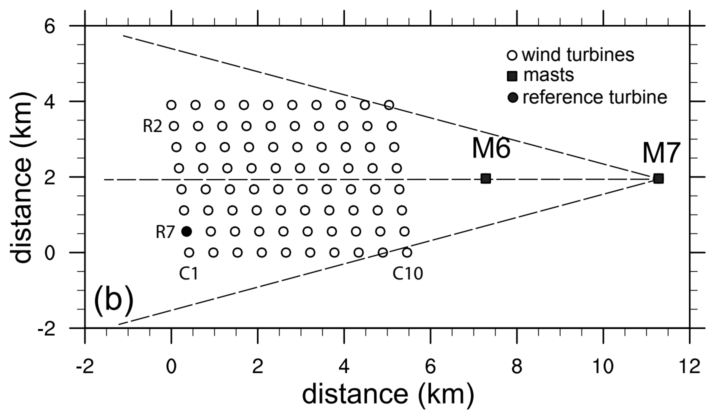
Volker, P. J. H. and Badger, J. and Hahmann, A. N. and Ott, S.: The Explicit Wake Parametrisation V1.0: a wind farm parametrisation in the mesoscale model WRF, *Geosci. Model Dev.*, 11, 8: 3715–3731, 2015.

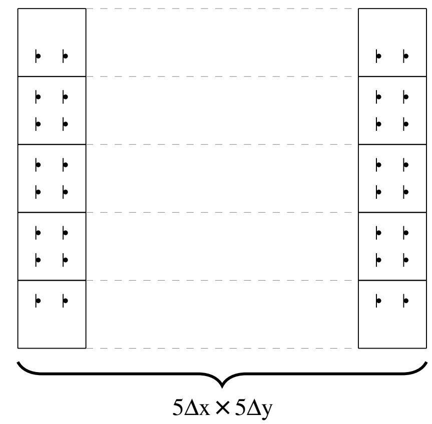
WRF-WF and EWP at Horns Rev I wind farm

- Wind farm: 80×2MW with 560 m separation
- Measurements at 2 km and 6 km (70 m amsl)
- Wind Speed 8±0.5 m/s, direction 270±15°

Model Set-up: Idealised case

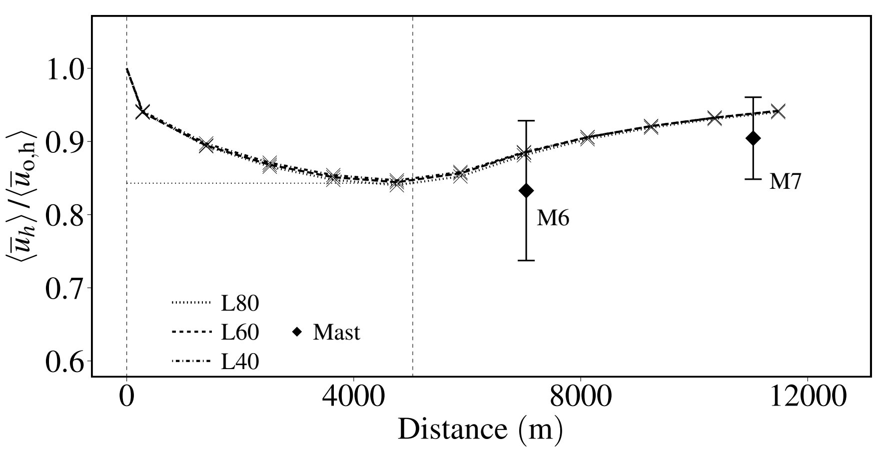
- 1120 m grid ⇒ 4 turbines per grid
- Seven wind directions between 255 and 285°



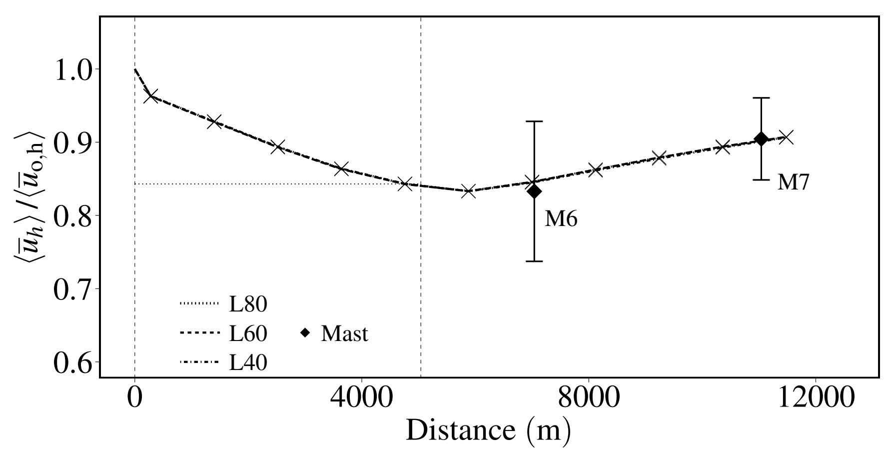


Velocity Deficit at Hub-height

WRF-WF

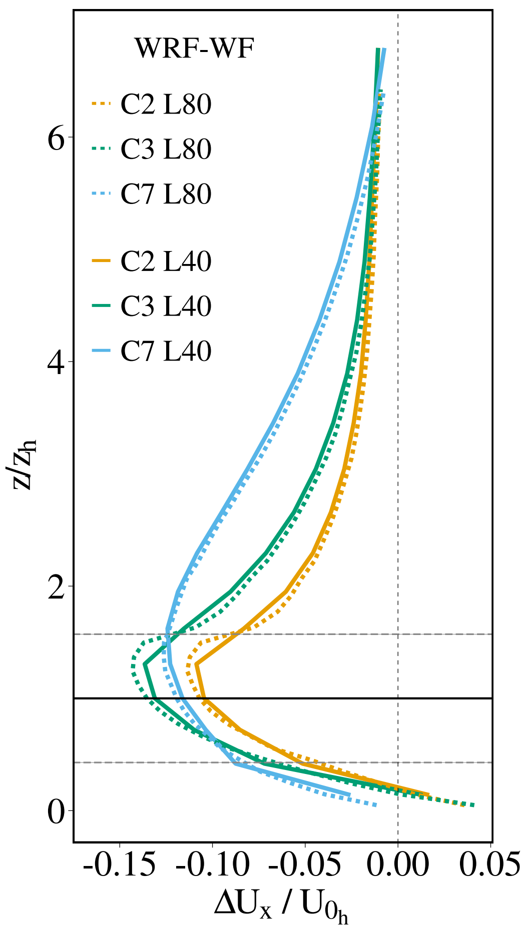


EWP

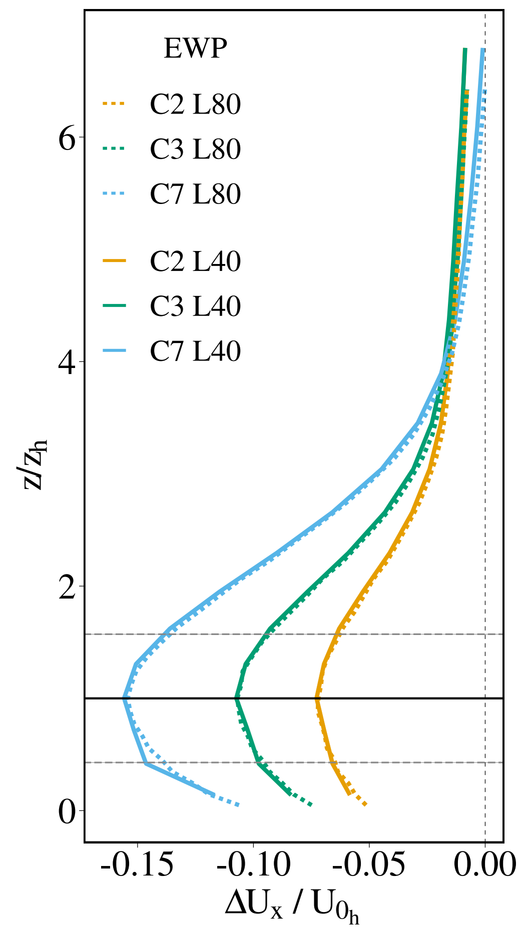


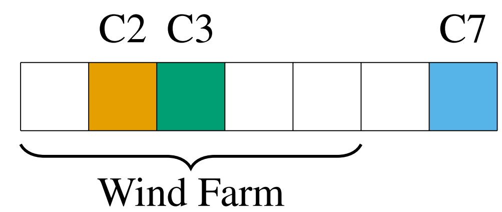
Normalised velocity deficit profile (neutral)

WRF-WF



EWP



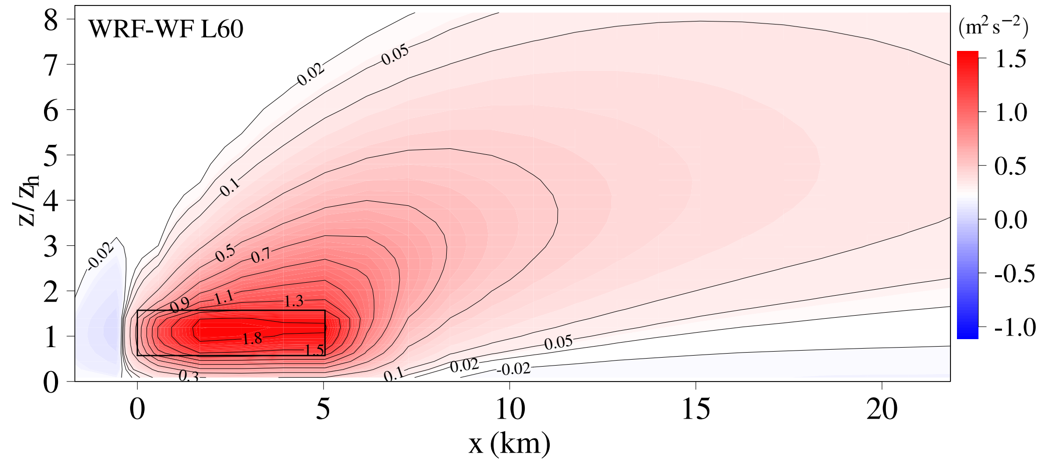


WRF-WF scheme:
- Accelerations at the lowest model level
- Lifting of the maximum deficit near to the upper blade tip

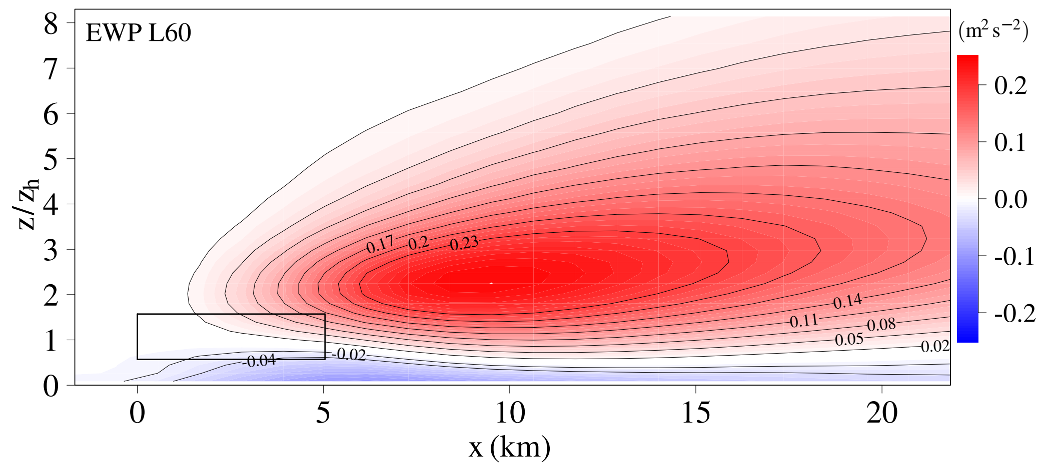
EWP scheme:
- Profile agrees with neutral LES simulations
- Less diffusive than WRF-WF scheme

Turbulence kinetic energy difference (neutral)

WRF-WF



EWP



WRF-WF scheme:

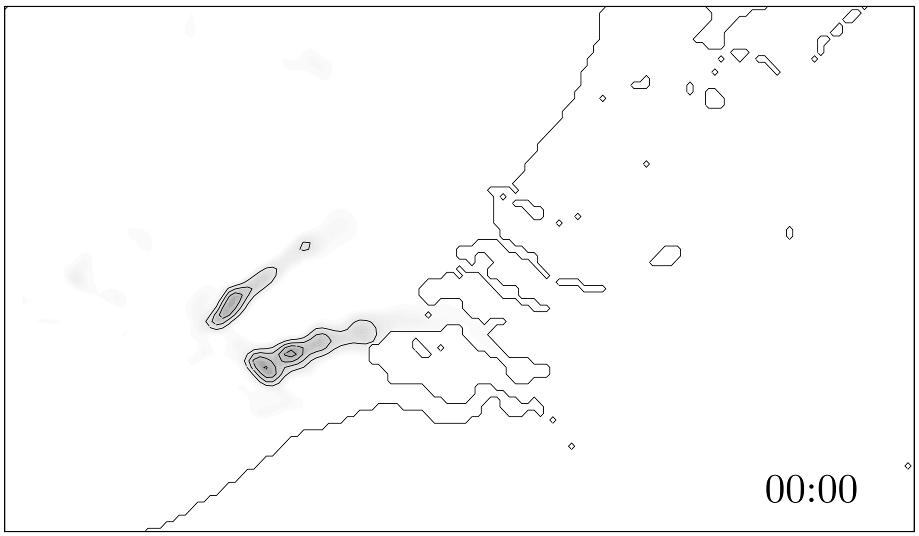
- Increased TKE from the lowest model level onwards due to $\langle \overline{p}_t \rangle$ and $\langle \overline{p}_s \rangle$
- Fast growing internal boundary layer

EWP scheme:

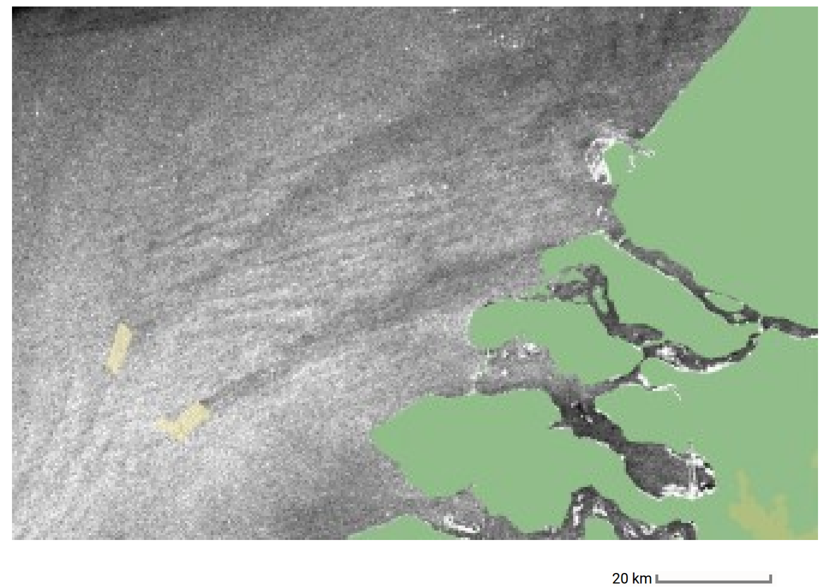
- Increased/decreased TKE above/below hub-height
- Slower internal boundary layer growth

Dynamical Modelling (EWP in wrf real)

WRF simulation after 2 days spin-up: From 00 UTC every 30 min the velocity deficit (Wind farm minus control) at 10 m.



Wake behind Belwind and Thornton wind farm 2013 July 1st 17:34 UTC (SAR image).



Advantage: WRF allows to study instantaneous flow (WS, T, Q)

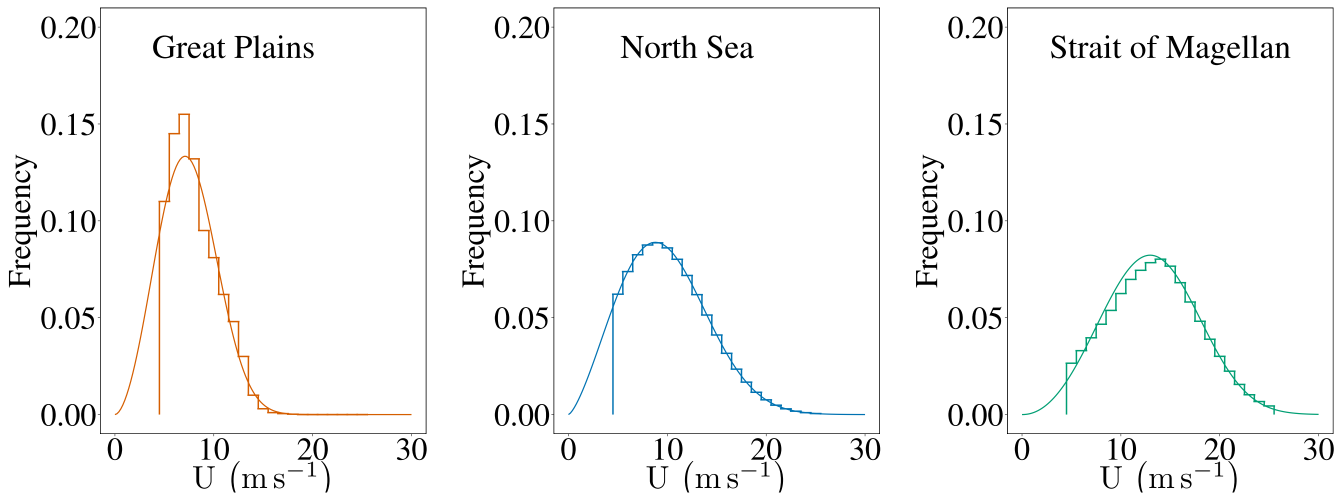
Disadvantage: No analytical study possible due to always changing conditions

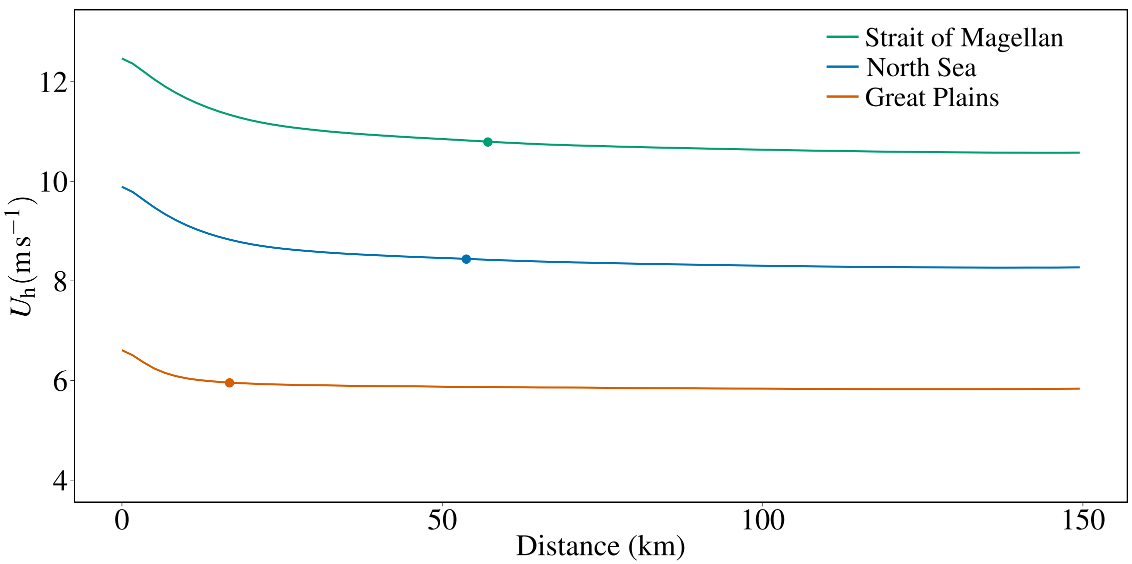
Statistical-Dynamical Modelling (wrf ideal)

Steady state simulations with Geostrophic wind forcing and neutral PBL

These simulations can be used to analyse the wind speed reduction analytically

Simulations for different wind speeds and roughness

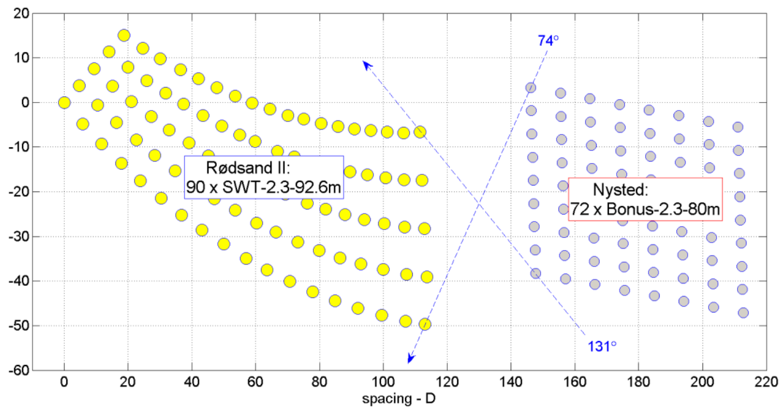




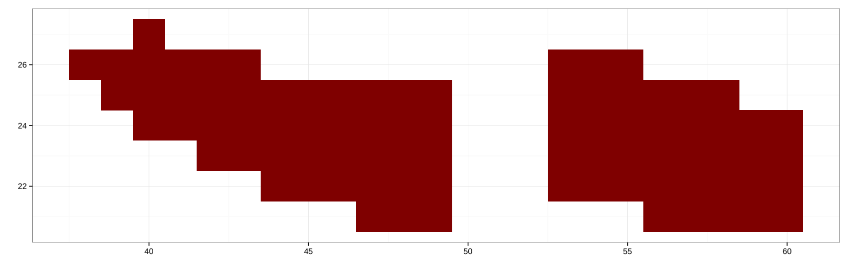
Example: We can relate optimal turbine spacing to wind conditions and roughness

Challenge: Irregular Wind farms

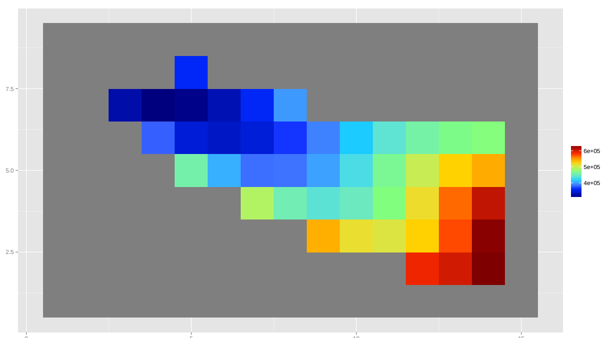
Rødsand II and Nysted layout

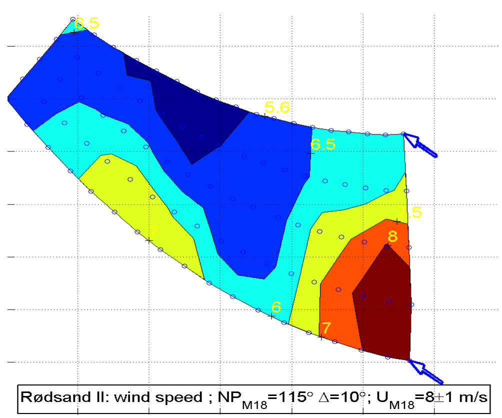


WRF layout (1 km grid)

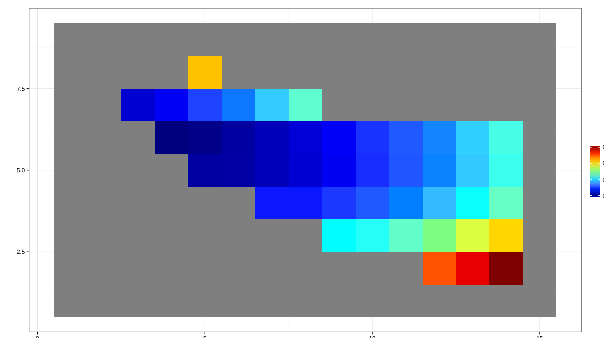


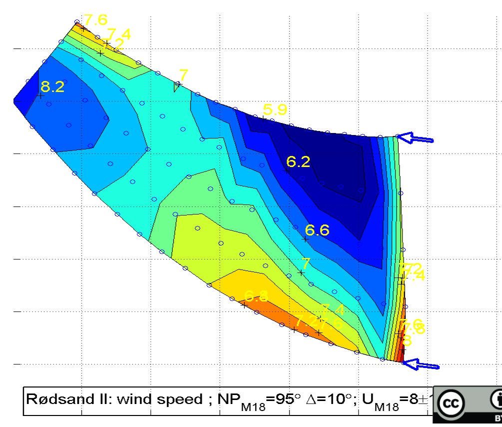
Power production: 115° and $\mathbf{U} = \mathbf{8}$ m/s





Power production: 95° and $\mathbf{U} = \mathbf{8}$ m/s





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Conclusion

Possible

- Simulate flow reductions behind wind farms
- For simple turbine configurations we can estimate flow reductions inside wind farm

Challenges

- Flow reduction within irregular wind farms
- Power estimation (local wind may be different from spatial average)
- EWP: more measurements are needed for initial length scale